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by

A. G. Zaslavskiy and R. A. Shipov

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

INVESTIGATION OF BLADE FLUTTER OF AXIAL COMPRESSORS BY THE DISCRETE-PHASE METHOD

Candidates of Technical Sciences A.G. Zaslavskiy
and R.A. Shipov

The flutter (self-oscillations) of blades of axial compressors can substantially limit the operational possibilities of the compressors [1 and 2]. Vibrations of this type appear in a limited region of conditions of the streamline flow of blades - in the zone of flutter. With the deepening into this zone the stresses in the blades are rapidly increased and can lead to their breakage. Owing to the difficulties in the conducting of experiments on turbomachines, the investigations of blade flutter are often conducted on foil cascades in wind tunnels [3 and 4]. However, similar experiments sufficiently reflect processes of the appearance and development of blade flutter of real blade rows. The development of the discrete-phase method of the noncontact measurement of blade vibrations [5] considerably simplifies the investigation of blade flutter of turbomachines, since sensors of the instrument ELURA [Electron-Beam Device for Recording Amplitude of Vibrations] maintain the efficiency for the extent of a considerably longer time than do the strain gauge sensing elements and slip ring devices; and the instrument records the vibrations simultaneously of all the blades of the blade row, which is difficult to carry out by their strain gauge measurements.

Some results of the investigations of flutter of blades of axial compressors by means of the instrument ELURA are given below. The experiments were conducted on five single-stage axial compressors with a diameter D_k = 320-360 mm and the relative diameter of the hub $\bar{d} \approx 0.4$. The elongation of the rotor blades was 2-2.5, and their relative thickness on the average radius is 4-6%. The blades were manufactured from steel or titanium. Two test stages had an input guide vane and three - the axial input of the flow, and one of them was tested with a rotating spinner. The last stage in another dimensionality (M 2.1:1) was also tested in the system of the natural multistage compressor. The obtained modes of the appearance of self-oscillations of blades were similar to the modes for a separate stage. Part of the experiments was conducted with the simultaneous use of strain-gauge measuring and the instrument ELURA. Since this instrument reliably recorded the moment of the appearance of the self-oscillations and the level of stresses, in a number of the tests it proved to be possible not to use the strain-gauge measurement. Revealed in all the investigated stages was the flutter of rotor blades according to the first flexural form*, which appeared in the modes of large angles of attack in a wide range of values of the number of normalized revolutions $\bar{n}_{np} = \bar{n}/\sqrt{T}$. The flutter frequency practically coincided with the dynamic frequency of the main tone of oscillations of the blades with the corresponding number of physical revolutions n, and, therefore, it is clear that in the overwhelming majority of the cases the flutter frequency proved to be not multiple to the number of revolutions, which made it possible to use the instrument ELURA in conformity with the method given in work [5]. According to their properties, the observed auto-oscillations can be classified as "stall flutter" [6]. The frequency of the oscillations of all the blades of the row with flutter was identical, in spite of certain differences of their natural frequencies. This

*Here we do not examine the flutter of blades with respect to higher forms observed on certain stages, which was also investigated by the instrument ELURA.

indicates the fact that the flutter is a loss of the dynamic stability of the whole row [ring] as a connected system of the blades. A large part of the aerodynamic and mechanical interaction (connectedness) of the blades in the process of the excitation of their vibrations was noted in a number of works [3, 7 and 8].

A considerable part of the studies of flutter (in particular, those examined in this article) can be conducted without a precise measurement of stresses in the blades, and therefore information only about the amplitudes of oscillations obtained by the instrument ELURA is sufficient. In cases when the determination of stresses is required, this can be fulfilled by means of the preliminary calibration of the instrument ELURA according to readings of strain gauges or with the use of the calculated dependence between the movements and stresses with the vibrations. It should be kept in mind that the dependence obtained experimentally in laboratory conditions can be used only for the approximation estimates, since with identical movements the stresses in the field of centrifugal forces are 1.5-2.5 times greater than for the nonrotating blade. The maximal stresses with flutter examined below reached 20-25 for steel and 12-15 kgf/mm^2 for titanium blades. Only the amplitudes of oscillations of blades will be subsequently examined. The flutter of the blade row is excited according to one of its natural forms of oscillations, the number of which is equal at least to the number of the blades. Understood by form of the oscillations is the totality of the relative amplitudes and phases of oscillations of all the blades. Since in the examined tests the phases of the oscillations were not measured, then subsequently understood by the form of oscillations of the blade row will be the distribution of only the relative amplitudes. It is natural that here it is not possible to note the different forms which are distinguished only by magnitudes of shifts in the phases, the existence of which is not excluded. Thus with the flutter of a uniform ring cascade, all the blades should oscillate with identical amplitudes, and the forms of the oscillations are different from each other by a shift in the phases between the adjacent blades equal to $\varphi = 2\pi q/z$, where q = 0, 1, 2, ..., z-1 [9].

In general, owing to the differences in the blades, all the natural forms of the oscillations have different distributions of amplitudes. However, two different forms can be accepted as one due to the insufficient accuracy of the measurement of amplitudes of oscillations, which is connected with the inevitable errors in the measurement and deciphering of the data, and also the presence of the vibration background. The belonging of two distributions of amplitudes, the mth and nth, to one or different forms of oscillations of the blade row can be defined by means of the correlation coefficient

$$k_{mn} = \frac{\sum_{j=1}^{z} A_{mj} A_{nj}}{\sqrt{\sum_{j=1}^{z} A_{mj}^2 \sum_{j=1}^{z} A_{nj}^2}},$$

where j is the blade number.

If the mth and nth distribution of amplitudes belongs to the one form, then with the absence of errors and background $\bar{A}_{mj} = \bar{A}_{nj}$, where $\bar{A}_j = A_j/A_{cp}$ is the relative amplitude; $A_{cp} = \frac{1}{z}\sum_{j=1}^{z} A_j$. In this case $k_{mn} = 1$. In actuality, even for distributions referring to one form, $k_{mn} \neq 1$, where the less A_{cp}, the greater k_{mn}, can be different from unity (since the role of the errors increases).

Figure 1 shows the dependence $k^*(A_{cp})$ giving an estimate of the resolving capacity of the used method of measurement of the amplitudes, where A_{cp} is the minimal mean amplitude for two comparable distributions.

If for the two distributions $k_{mn} < k^*$, then they belong to different forms; otherwise, the resolving capacity of the method is insufficient in order to make any definite conclusion. Subsequently, the distributions for which $k_{mn} \geq k^*$ will belong to one form of oscillations of the row. The curve of Fig. 1 is obtained on the basis of the determination of the coefficient k_{mn} for a large number (>100) pairs of distributions, clearly belonging to one form of oscillations, for example, obtained with the deepening into the zone of the flutter by means of a smooth change of only the angle of attack or only air density with constant values of the remaining parameters.

Figure 2 shows four forms of oscillations obtained on one of the specimens of the stage tested in the compressor system. All these forms had practically identical excitability, i.e., they appeared under slightly differing conditions; the frequency of the auto-oscillations for all forms was also identical. Some blades having, with the oscillations in the same forms, small amplitudes, with oscillations in different forms have amplitudes which are close to the maximal. For other specimens of this stage (in all seven of them were tested), forms of the oscillations were different from those given in Fig. 2. The obtained forms of flutter wer were distinguished by the form of distributions of amplitudes and scattering A_{max}/A_{min}, the magnitude of which was changed from 1.5 to 5. For certain single-stage compressors the scattering of the amplitudes reached 8-12, which exceeds the maximal values known earlier [10].

In spite of the considerable scattering, the amplitudes of the adjacent blades in the overwhelming majority of the cases differed relatively little, which is the result of the connectedness of the oscillations. Hence it is possible to make an important practical conclusion: in the investigation of the auto-oscillations by means of the strain gauging of a limited number of blades, it is necessary to distribute the straingauge sensors uniformly over the circumference of the ring, since here the probability of recording stresses close to the maximal is increased.

As is known, the critical parameters of flutter of the blade row substantially depends on its frequency heterogeneity [1]. It would be possible to expect any connection between the distributions of frequencies of the blades and amplitudes of their oscillations. The presence of such a connection could be indicated by the closeness to unity or -1 of one of the coefficients of the cross-correlation of these distributions

$$\varkappa_q = \frac{1}{z\sigma_{\bar f}\sigma_{\bar A}} \sum_{j=1}^{z} (\bar f_{j+q} - 1)(\bar A_j - 1),$$

where σ is the mean quadratic deviation.

For distributions of amplitudes shown on Fig. 2 and the corresponding distribution of the frequencies on Fig. 3 max $|\varkappa_q| = 0.4$.

i.e., the connection between the distributions of frequencies and amplitudes is absent. This connection was absent in all remaining cases with the exception of those when values of frequencies of the blades were smoothly changed along the row. For such rows there existed the dependence between the distributions of frequencies and amplitudes, which is indicated by the form of the distributions (Fig. 4) and values of coefficients of correlation $|\varkappa q|_{max} = 0{,}85$. Although the scattering of the frequencies of blades of the row determines the scattering of amplitudes of the oscillations, the magnitudes of these scatterings are considerably different. The relative span of the amplitudes for tests of the rows exceeded the span of frequencies 10-60 times, and the ratio $\sigma_{\lambda}/\sigma_{f}$ was equal to 5-30.

It should be noted that in separate cases with an increase in A_{cp} a change in the form of the oscillations of the row occurred. In connection with the fact that this phenomenon was noted only with rather high values of A_{cp}, i.e., dangerous stresses, it was not specially investigated.

As far as the authors know, the cited data are the first experience of an investigation of natural forms of oscillations of blade rows in a flow. Further studies should lead to the establishment of more profound regularities. In particular, by such means there can be obtained information about the aerodynamic forces of the interaction of the blades, which as yet cannot be obtained by other methods.

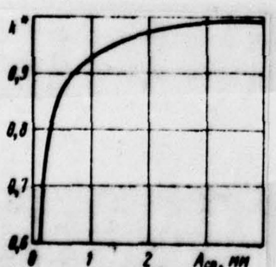

Fig. 1. Effect of the mean amplitude of oscillatons of the blades on the resolution of the method of measurements

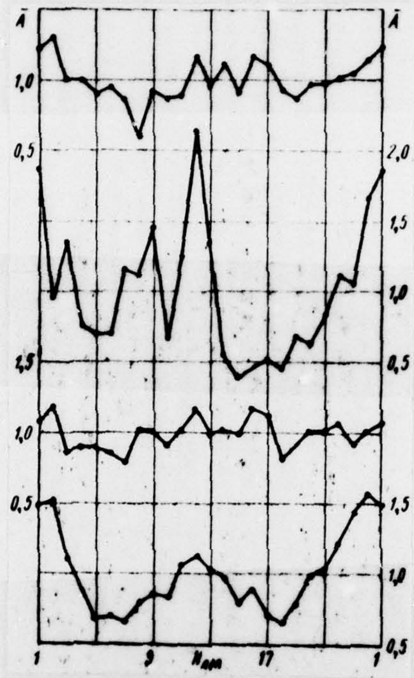

Fig. 2. Four different forms of oscillations of the blade row obtained on one specimen of the rotor blade

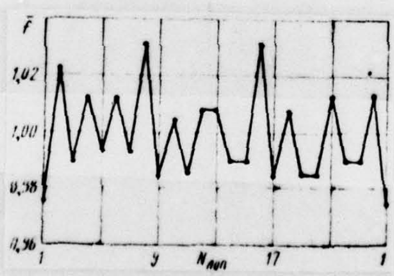

Fig. 3. Distribution of static natural frequencies of blades of the rotor, the results of the tests of which on flutter are given in Fig. 2

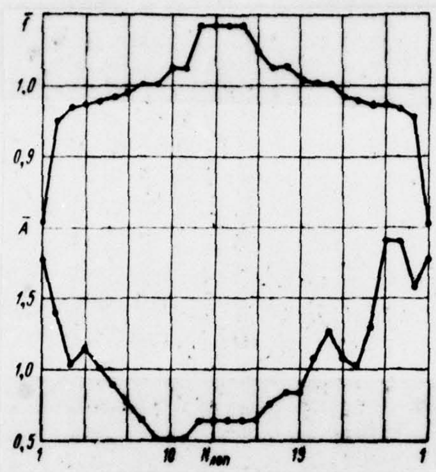

Fig. 4. Static natural frequencies of the blades and amplitudes of flutter with special arrangement of the blades in the web [disk]

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